Deltares

Maximum sea state wave estimation

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with contributions from:

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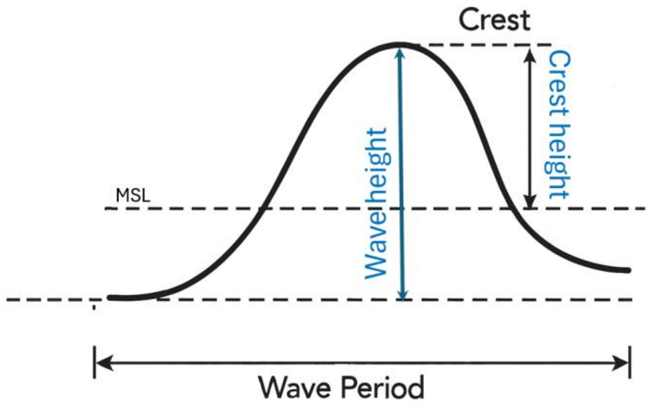
4TH INTERNATIONAL WORKSHOP ON WAVES, STORM SURGES, AND COASTAL HAZARDS
Incorporating the 18th International Waves Workshop

Motivation

One critical factor in the design and longevity of offshore wind farms is the accurate determination of the maximum individual wave height and associated wave period and crest height with a 50-year return period. The current practice (2008 onwards) in the determination of extreme individual wave conditions is to resort to return value estimates of significant wave height and of the associated spectral periods in combination with individual wave height distributions and empirical formulations to determine the maximum individual wave height and associated wave period and crest height. Given the wealth of available dedicated offshore metocean campaign data, the current practice could be validated.

Objective

Validate current practice estimates of maximum individual wave height and associated wave period and crest height using observations available from measurement campaigns at offshore wind farm areas.



- *Wave Height (H):* The vertical distance between the crest (highest point of the wave) and the trough (lowest point of the wave).
- *Wave Period (T):* The time (not distance) between two successive wave crests (or troughs) passing a fixed point.
- *Crest Height:* The vertical distance from the still water level (mean sea level) to the wave crest.

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Maximum individual wave height – Deviations from the Rayleigh distribution

It has long been established that the Rayleigh distribution over-predicts the largest waves in realistic sea-states (Longuet-Higgins, 1980; Forristall, 1984; Tayfun, 1990; Battjes and Groenendijk, 2000; Goda, 2010, Kampadakis et al. 2022):

- In deep water, models seek to account for this overprediction by incorporating finite spectral bandwidth effects.
- In regions with depth-induced breaking, models seek to account for this overprediction by incorporating depth effects.
- Our standard practice is to apply the Battjes and Groenendijk (B&G) distribution.

1st Goal: Verify to which extent deviations from the Rayleigh distribution are observed in offshore wind zones and whether the use of the B&G distribution is justified.

Period of maximum wave height

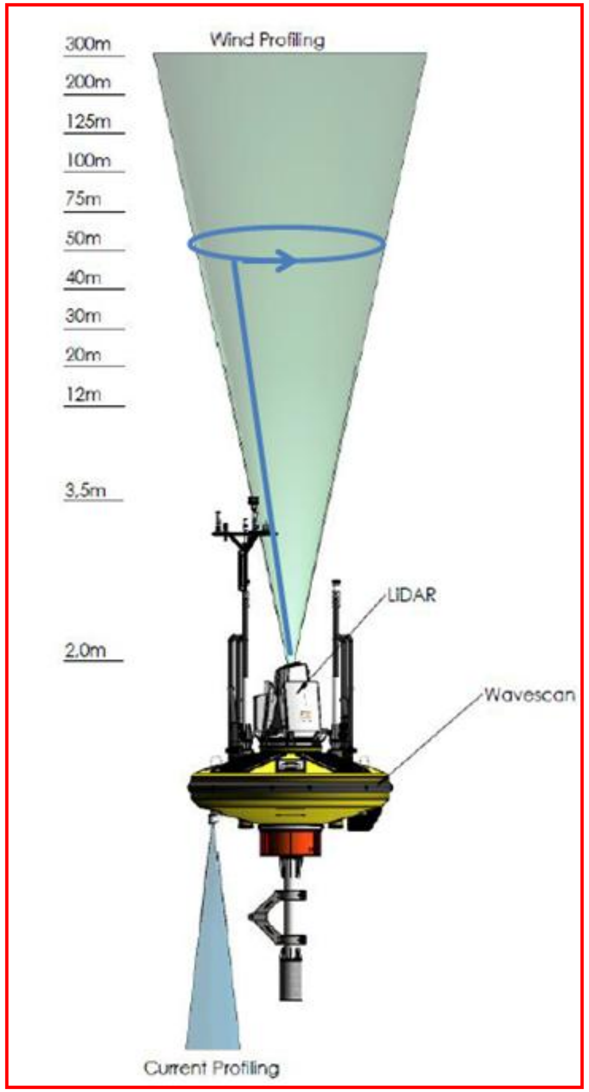
Goda (1978) has shown, based on an analysis of 89 measurements (a sample considered large for the time), that the most likely wave period associated with the highest waves in a sea state (T_{Hmax}) is closely related to the peak wave period (T_p). According to Goda this wave period is 0.9 to 1.0 times T_p.

Our standard practice is to take T_{Hmax} equal to T_p.

2nd Goal: Verify whether T_{Hmax} can be considered approximately equal to T_p

Goda, Y., 1978: The observed joint distribution of periods and heights of sea waves. In Proc. 16th Int. Conf.on Coastal Engineering, Hamburg. ASCE, New York, pp. 227-246.

Field measurements
Fugro's SEAWATCH Wind LiDAR Buoys



- Wavesense 3: 3-directional wave sensor and datalogging unit (timeseries duration of 1024 s ≈ 17 min);
- Xsens 3-axes motion sensor;
- Gill Windsonic M acoustic wind sensor;
- Vaisala PTB330A air pressure sensor;
- Vaisala HMP155 air temperature and humidity sensor;
- Nortek Aquadopp 600kHz current profiler; and
- ZephIR 300S LiDAR.

Currently there are more than 20 years (combined from 2019 onwards) of data from 1 to 2 years campaigns carried out to support the offshore wind development and tendering.

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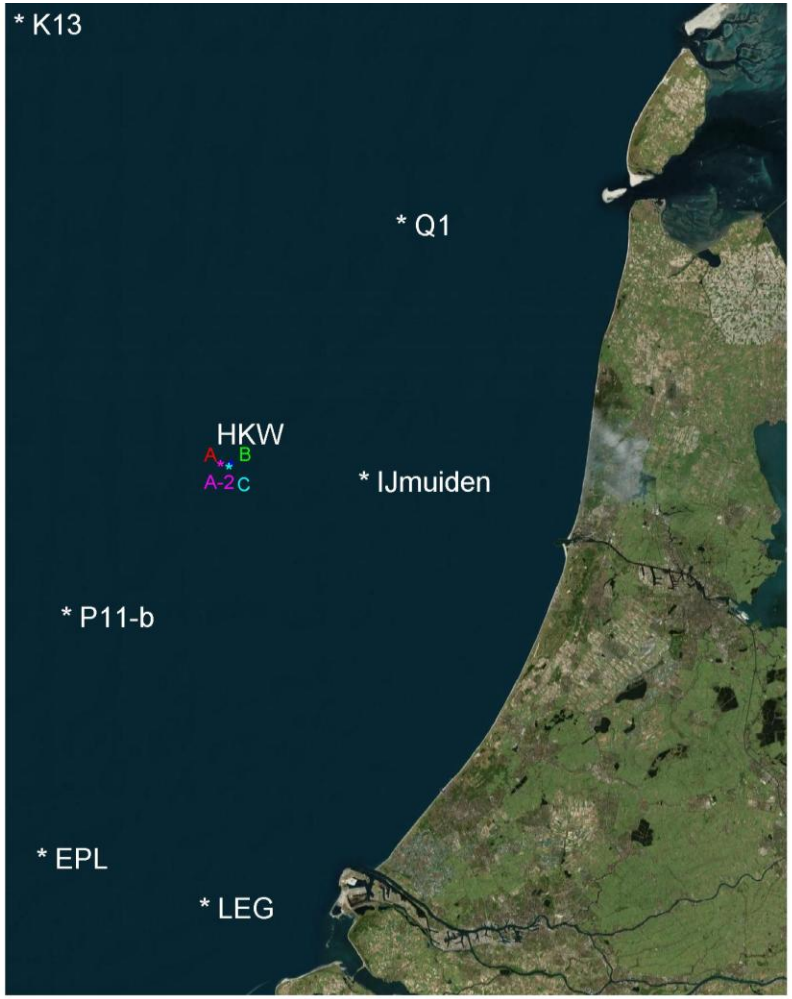
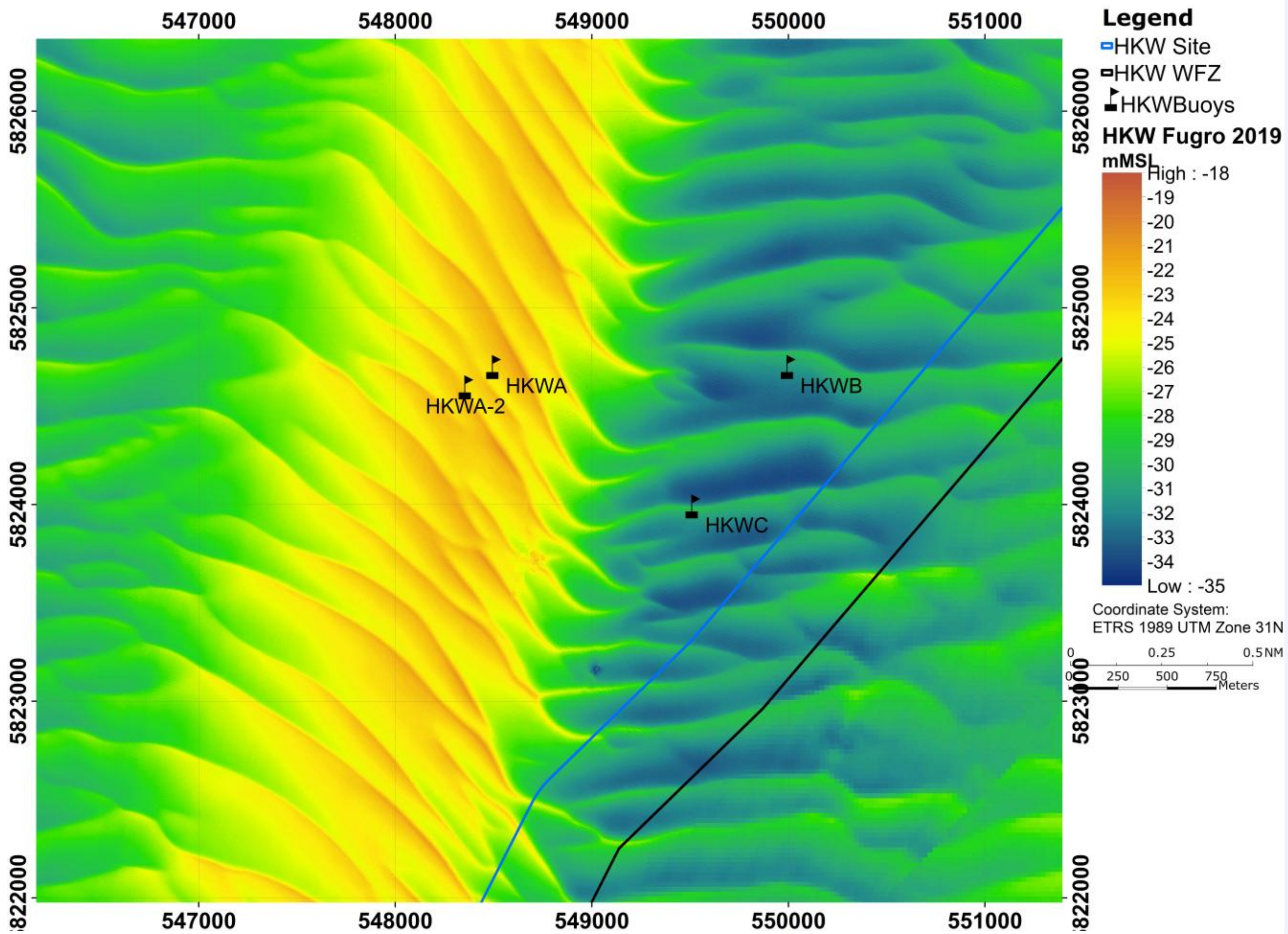
HKW (2019-2021)

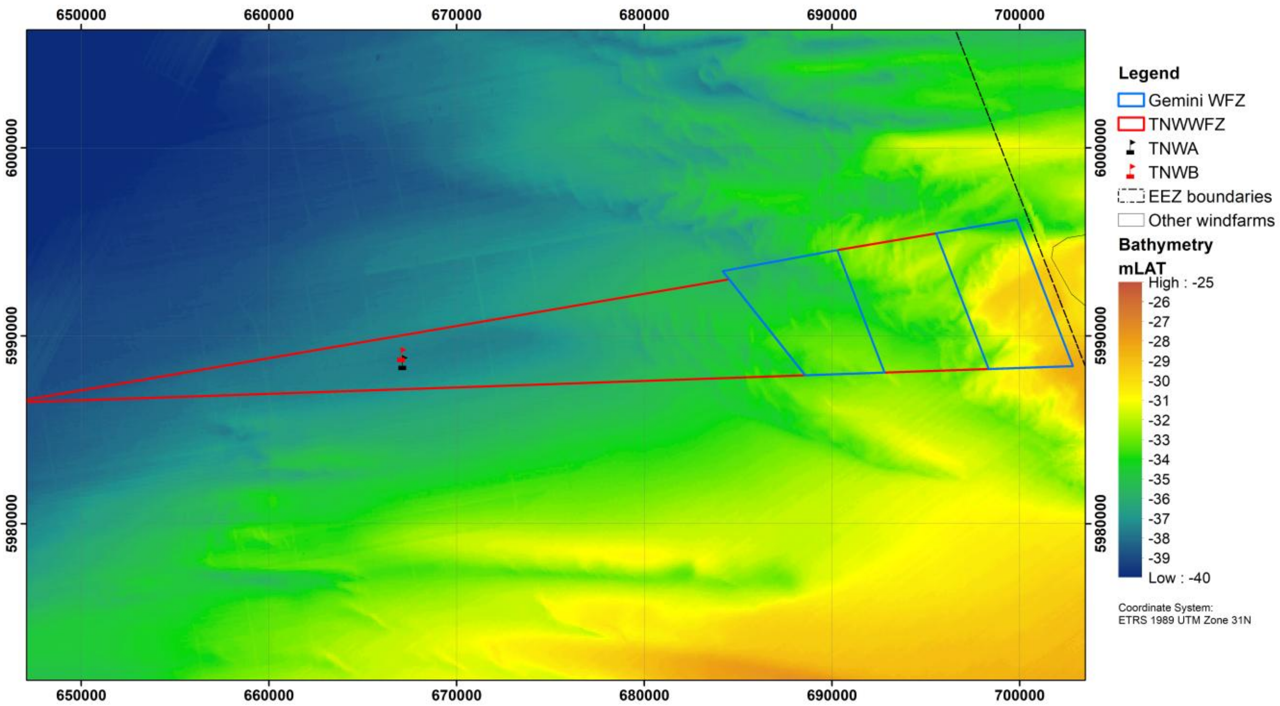
Station	Longitude (E)	Latitude (N)	Easting (m)	Northing (m)	Depth (mMSL)
HKWA	3°42.937'	52°34.211'	548500	5824700	23.1
HKWA-2	3°42.812'	52°34.156'	548400	5824600	22.8
HKWB	3°44.264'	52°34.203'	550000	5824700	30.8
HKWC	3°44.083'	52°33.935'	549800	5824200	31.2





TNW (2019-2021)

Station	Longitude (E)	Latitude (N)	Depth (mMSL)
TNWA and TNWA-2	5.5502°	54.0181°	≈ 38
TNWB and TNWB-2	5.5498°	54.0218°	≈ 38

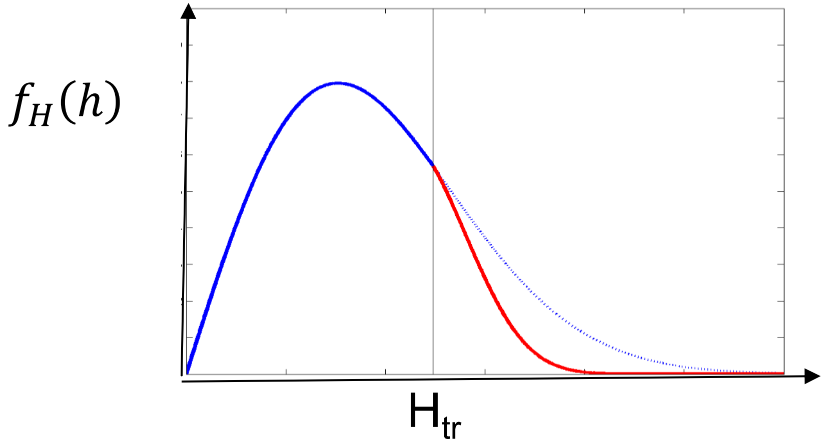


Maximum individual wave height – Deviations from the Rayleigh distribution

For regions with depth-induced breaking various alternatives to the Rayleigh distribution have been proposed which impose restrictions on the distribution of higher individual wave heights in the sea state.

One of the most used of these distribution is the Battjes and Groenendijk, distribution given by a composite Weibull distribution

$$P(H \leq h) = \begin{cases} 1 - \exp\left[-\left(\frac{h}{H_1}\right)^2\right] & h \leq H_{tr} \\ 1 - \exp\left[-\left(\frac{h}{H_2}\right)^{3.6}\right] & h > H_{tr}. \end{cases}$$



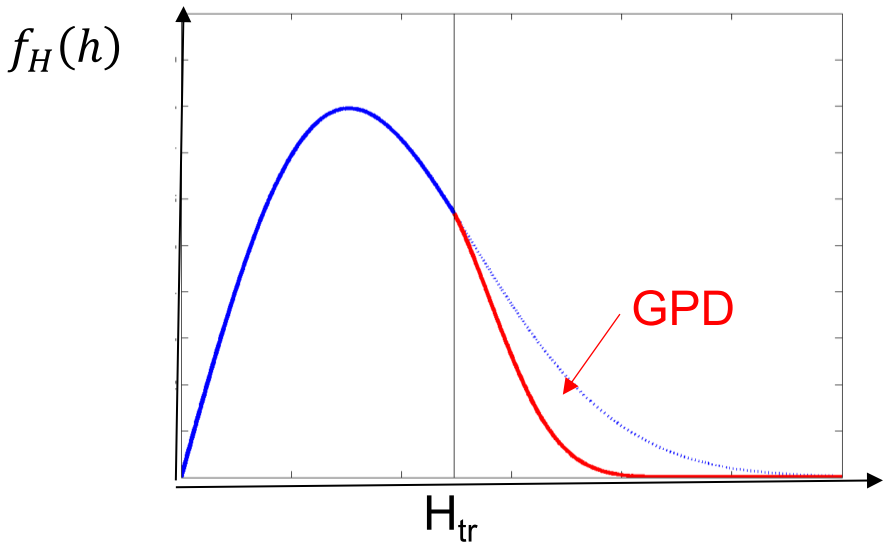
On the basis of fits to flume measurements, Battjes and Groenendijk (2000) define the transitional wave height as a function of the foreshore slope α and the water depth d.

Battjes, J.A. and H.W. Groenendijk, 2000: Wave height distributions on shallow foreshores, Coastal Engineering. 40, 161-182.

Maximum individual wave height – Deviations from the Rayleigh distribution

Using more data Wu et al. (2016) proposed a distribution, taking the form of a (truncated) Weibull distribution to the left and a generalised Pareto distribution to the right. The parameters do not depend on the bottom slope as in the Battjes and Groenendijk distribution, but on the wave period (and steepness).

This distribution commonly known as the LOWISH distribution, since it has been derived in a homonymous Joint Industry Project.



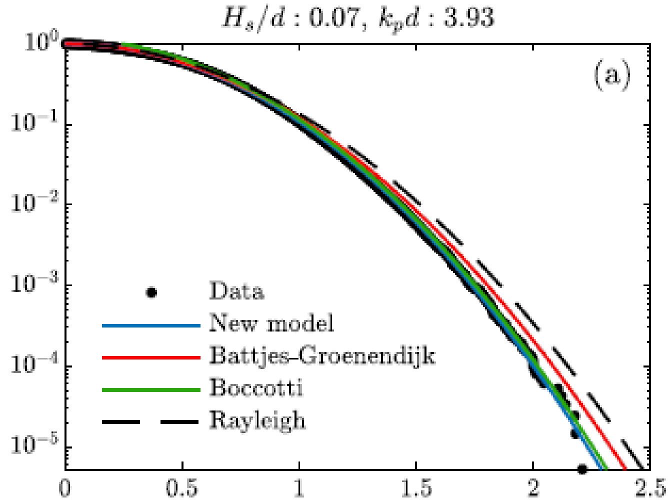
Wu, Y, D. Randell, M. Christou, K. Ewans and P. Jonathan, 2016: On the distribution of wave height in shallow water, Coastal Engineering, 111, 39–49.

Maximum individual wave height – Deviations from the Rayleigh distribution

Karmpadakis et al. derived their intermediate and shallow water depths and it incorporates explicitly the effects of nonlinearity, reduced effective water depth and finite spectral bandwidth.

The parameters depend on the significant wave height, peak wave period, peak enhancement factor and depth.

$$P(H \leq h) = 1 - \exp\left[-A\left(\frac{h}{H_{rms}}\right)^{\kappa}\right]$$



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Karmpadakis, I, C. Swan, and M. Christou, 2022: A new wave height distribution for intermediate and shallow water depths, Coastal Engineering, 175. 104130.

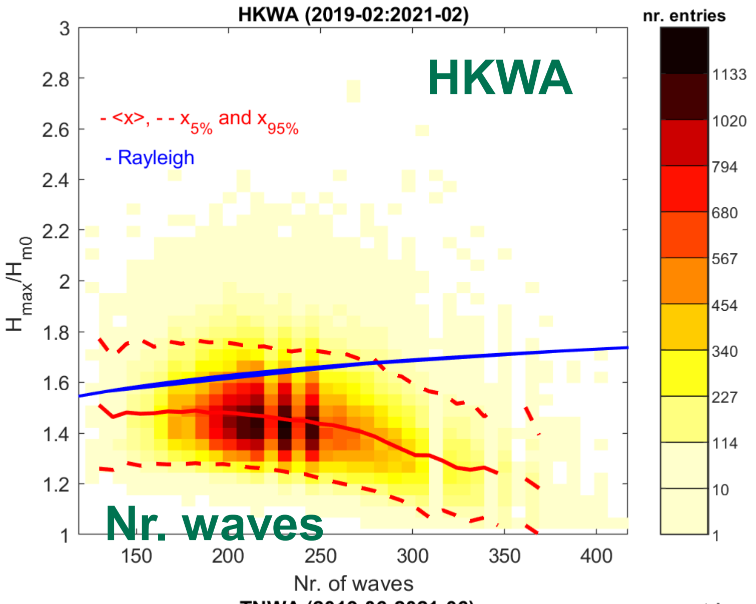
Crest height – Determined using the Rienecker & Fenton (1981) method

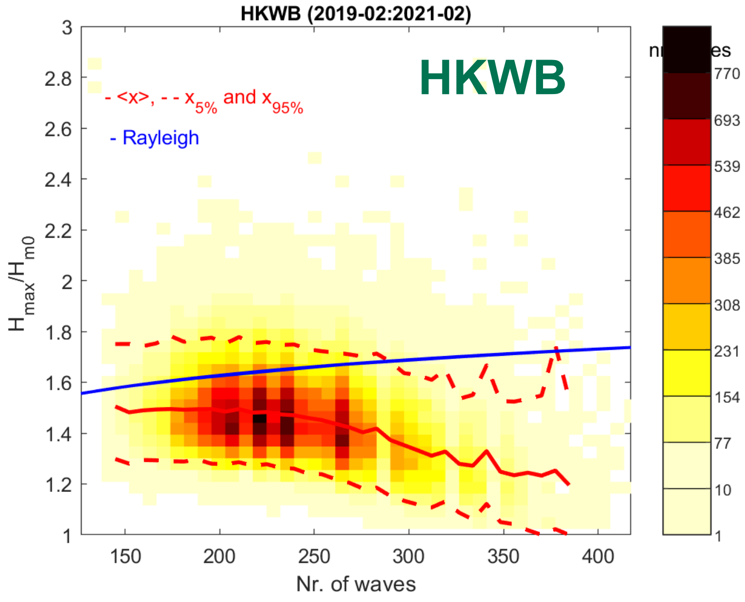
Rienecker & Fenton’s method builds a Fourier representation of the wave, plugs it into the exact free-surface boundary conditions, and then solves the resulting nonlinear equations numerically — > a highly accurate, truncated Fourier solution for steady periodic waves.

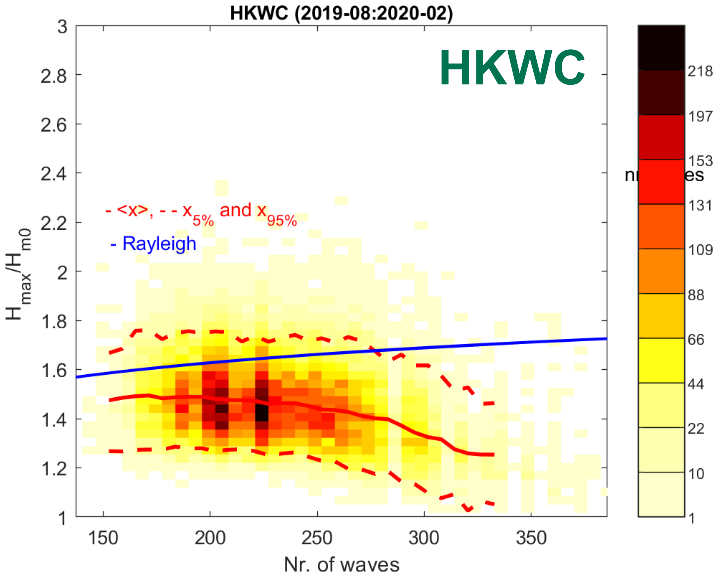
Because it solves the full nonlinear free-surface problem with very few assumptions (just truncating the Fourier series), it gives highly accurate wave shapes and kinematics across a wide range of depths and wave heights.

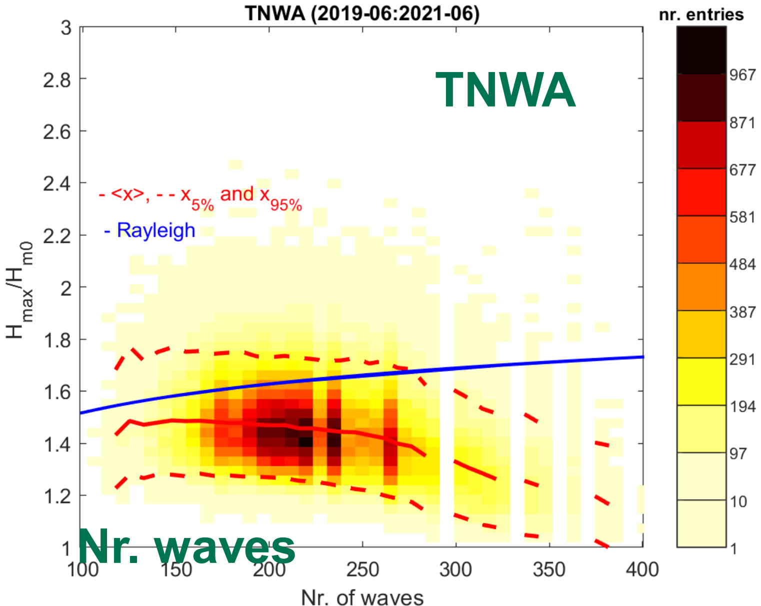
Rienecker, M.M. and J.D. Fenton, 1981: A Fourier approximation method for steady water waves. J. Fluid Mechanics, 104, 119–137.

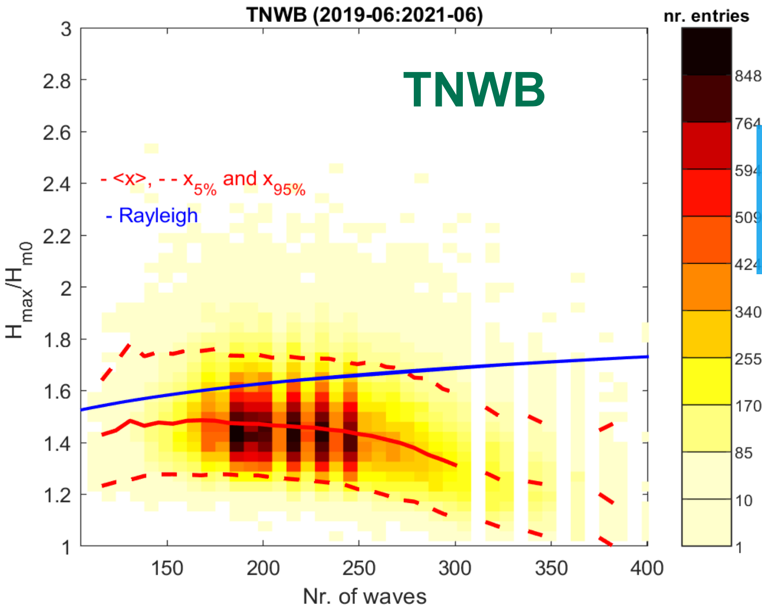
Observed relation between H_{max}/H_{m0} and Nwaves





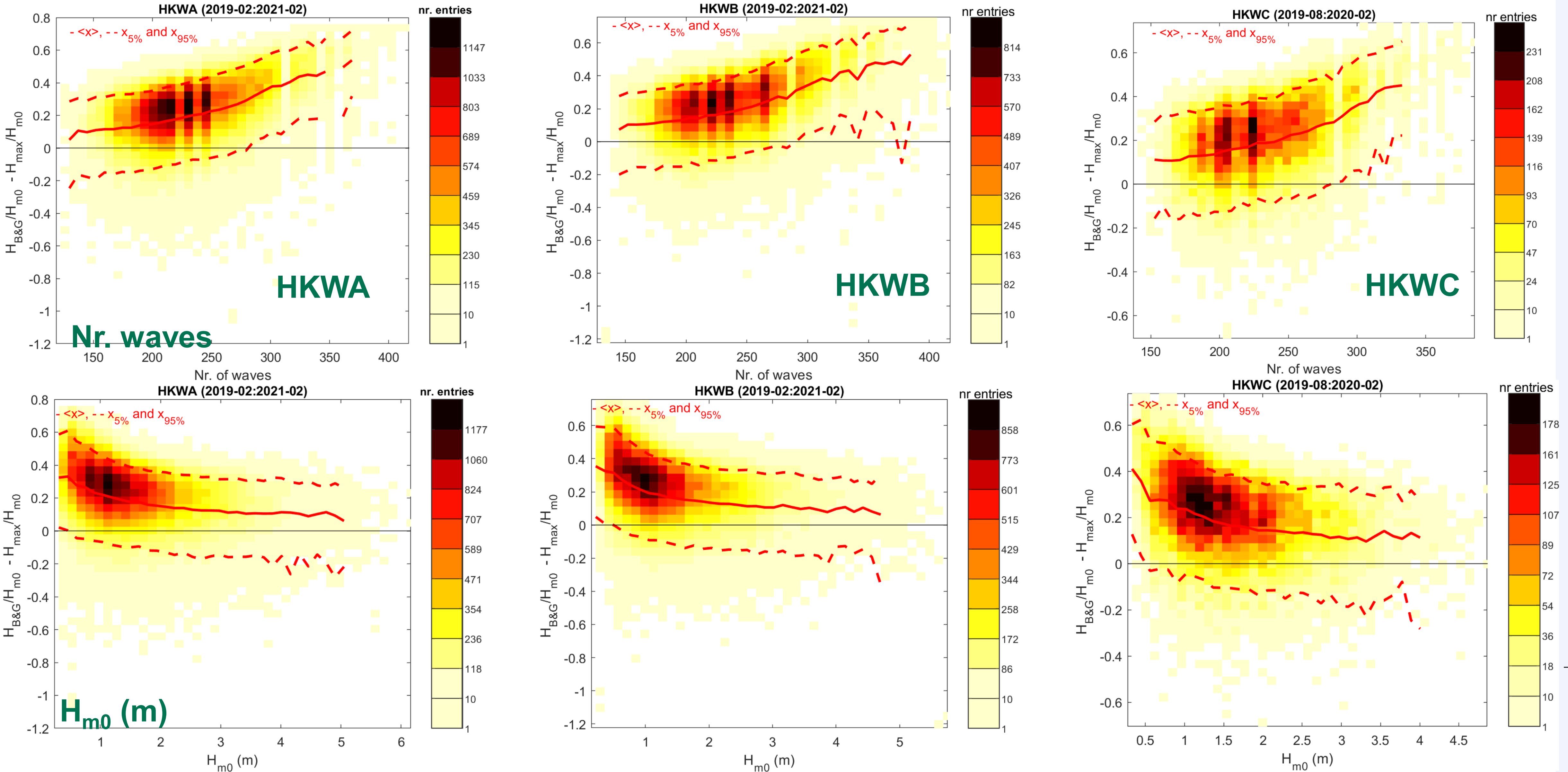




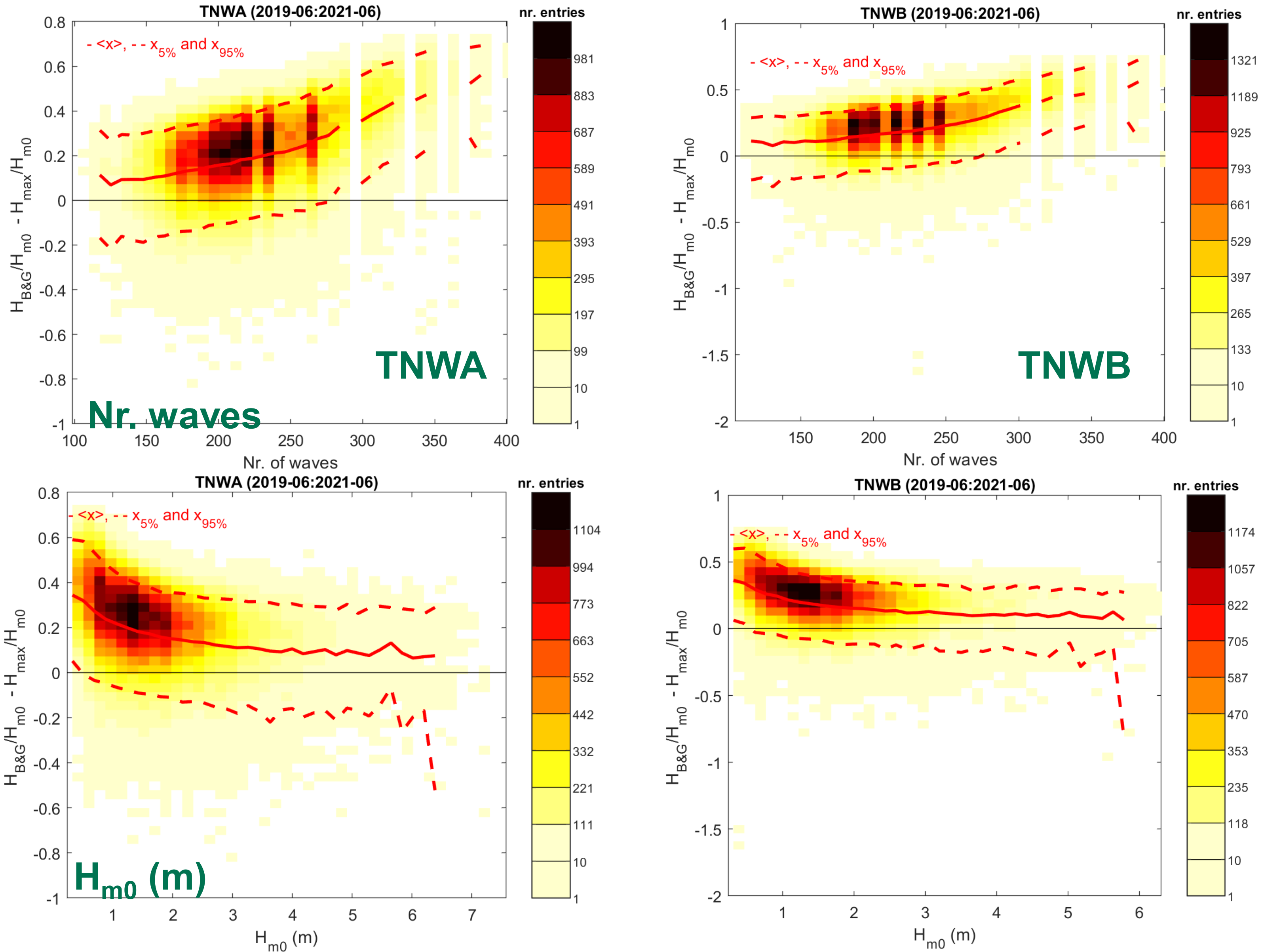


Rayleigh leads to overestimates of H_{max}/H_{m0} ratio.

Bias in B&G H_{max}/H_{m0}

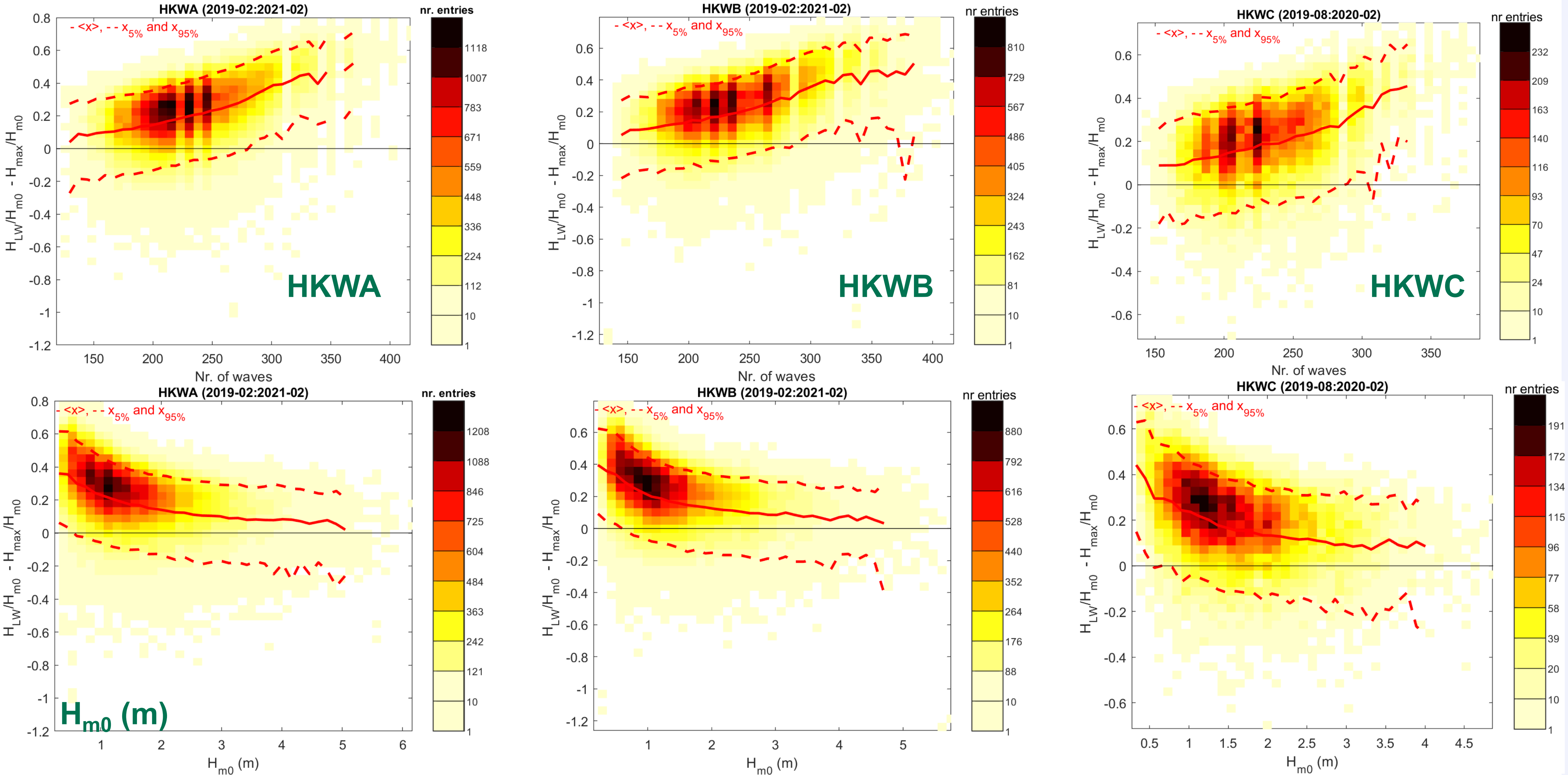


Bias in B&G H_{max}/H_{m0}

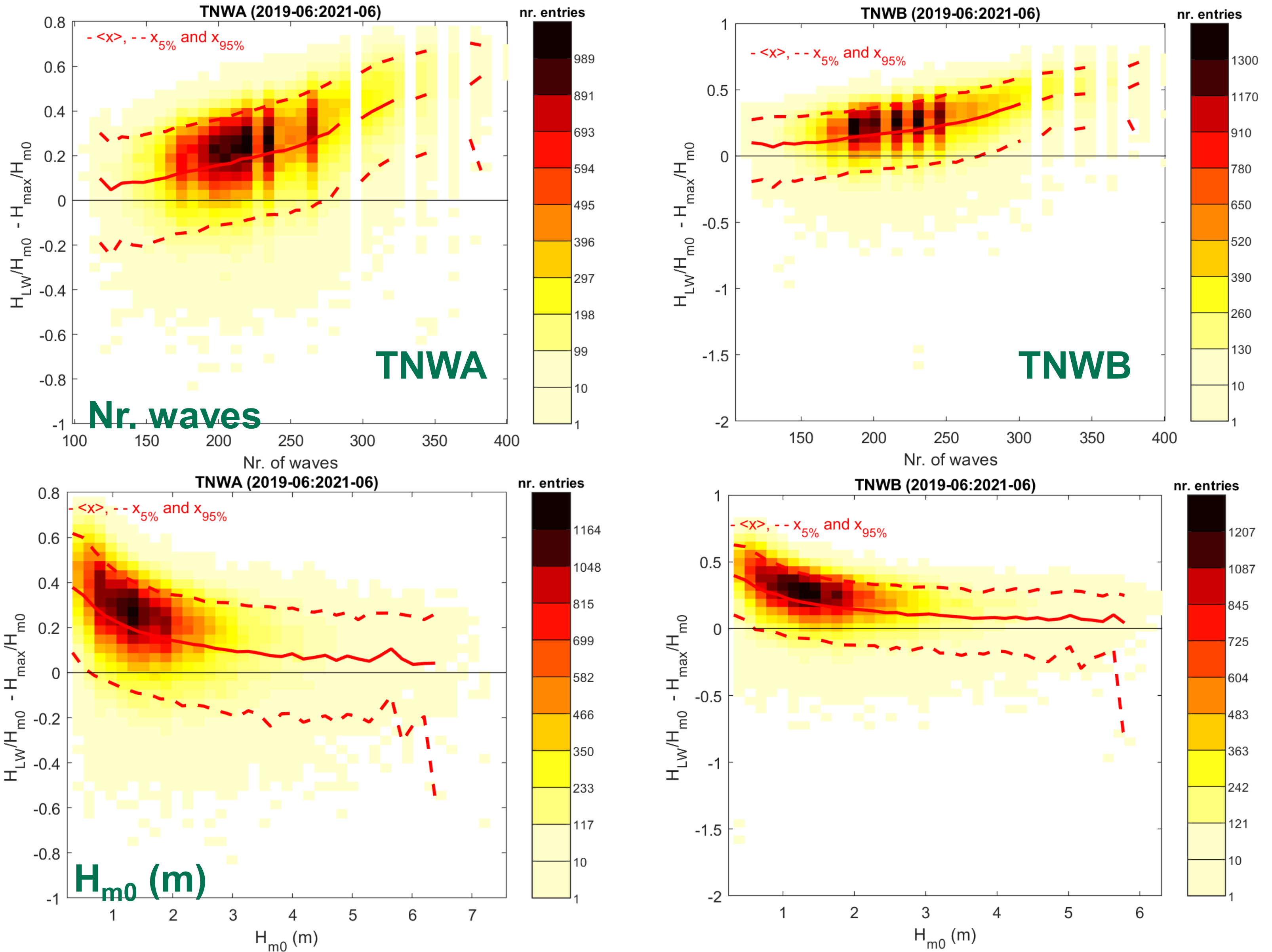


B&G positive bias (overestimation of H_{max}) than increases with the number of waves and decreases with H_{m0}.

Bias in LOWISH H_{max}/H_{m0}

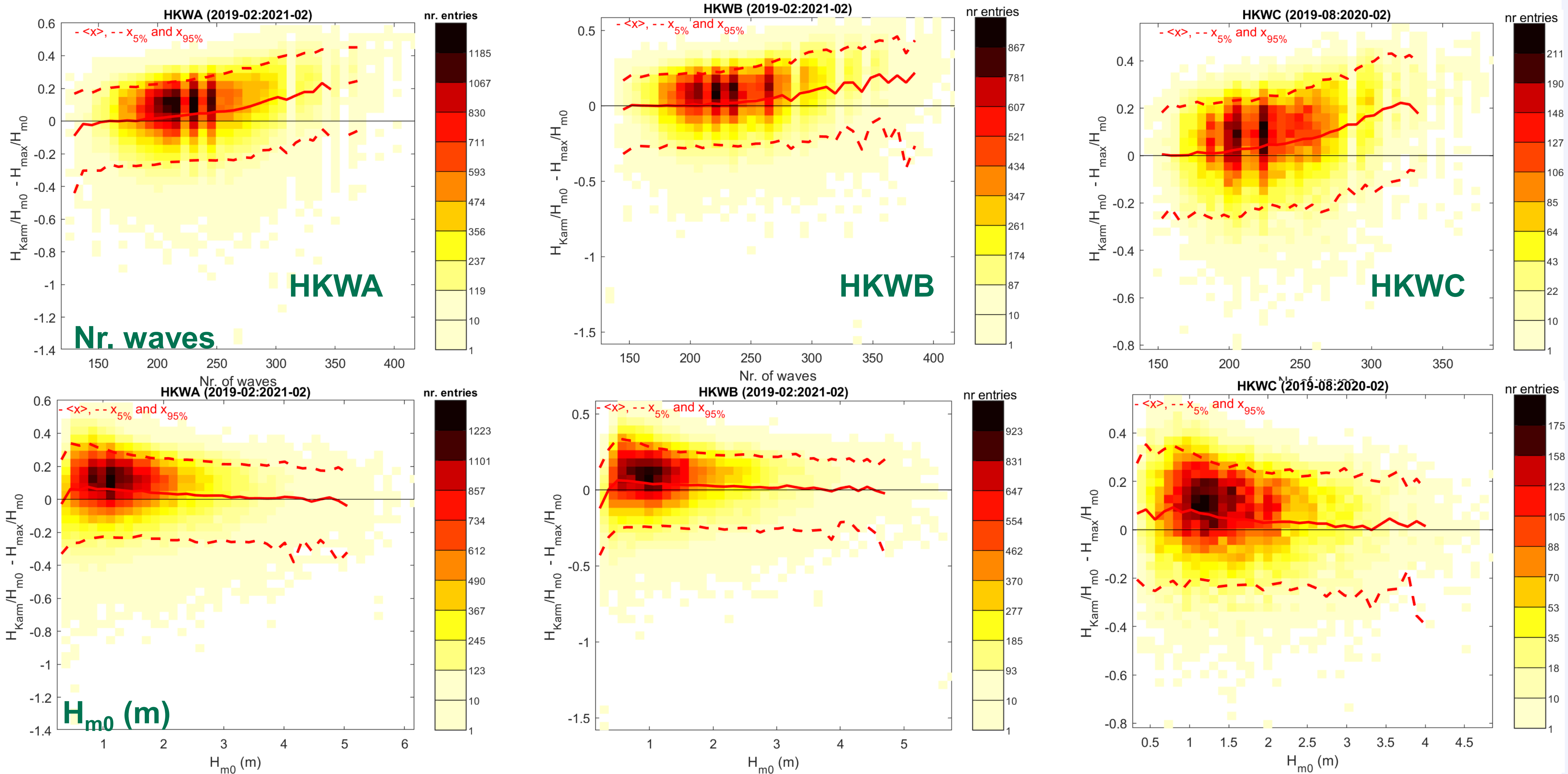


Bias in LOWISH H_{max}/H_{m0}

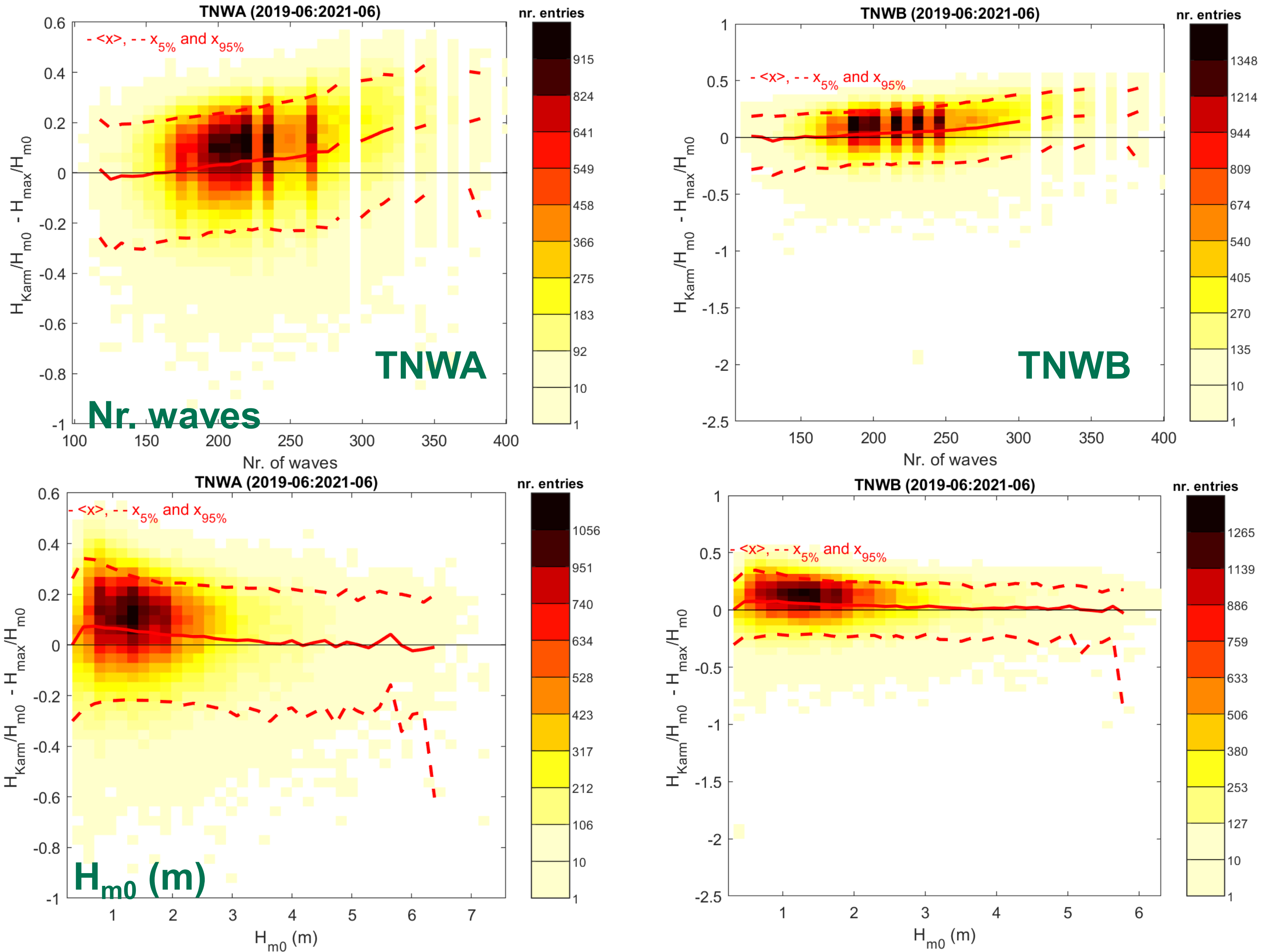


LOWISH positive bias (overestimation of H_{max}) than increases with the number of waves and decreases with H_{m0}.

Bias in Karmpadakis et al. H_{max}/H_{m0}

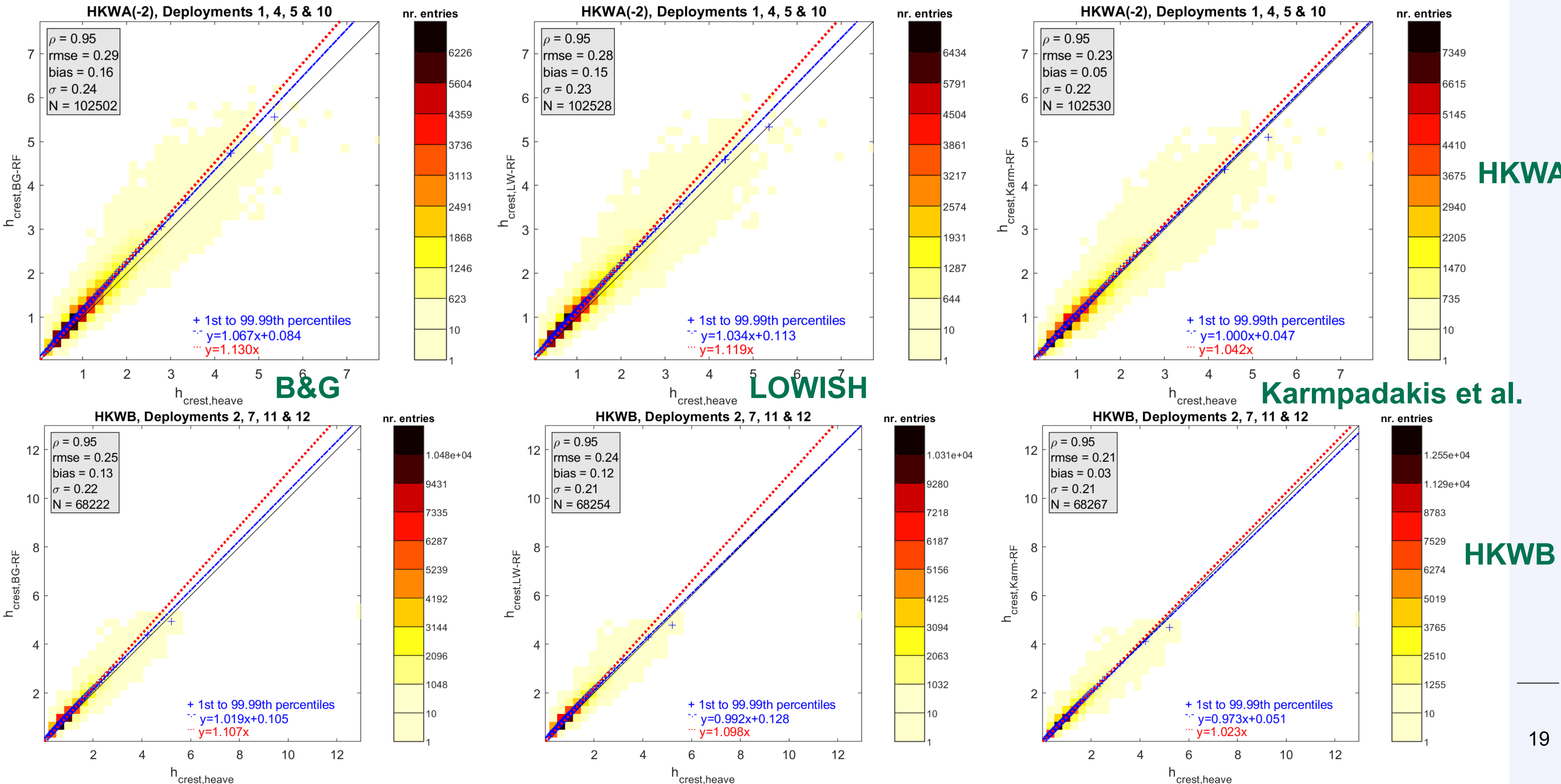


Bias in Karmpadakis et al. H_{max}/H_{m0}

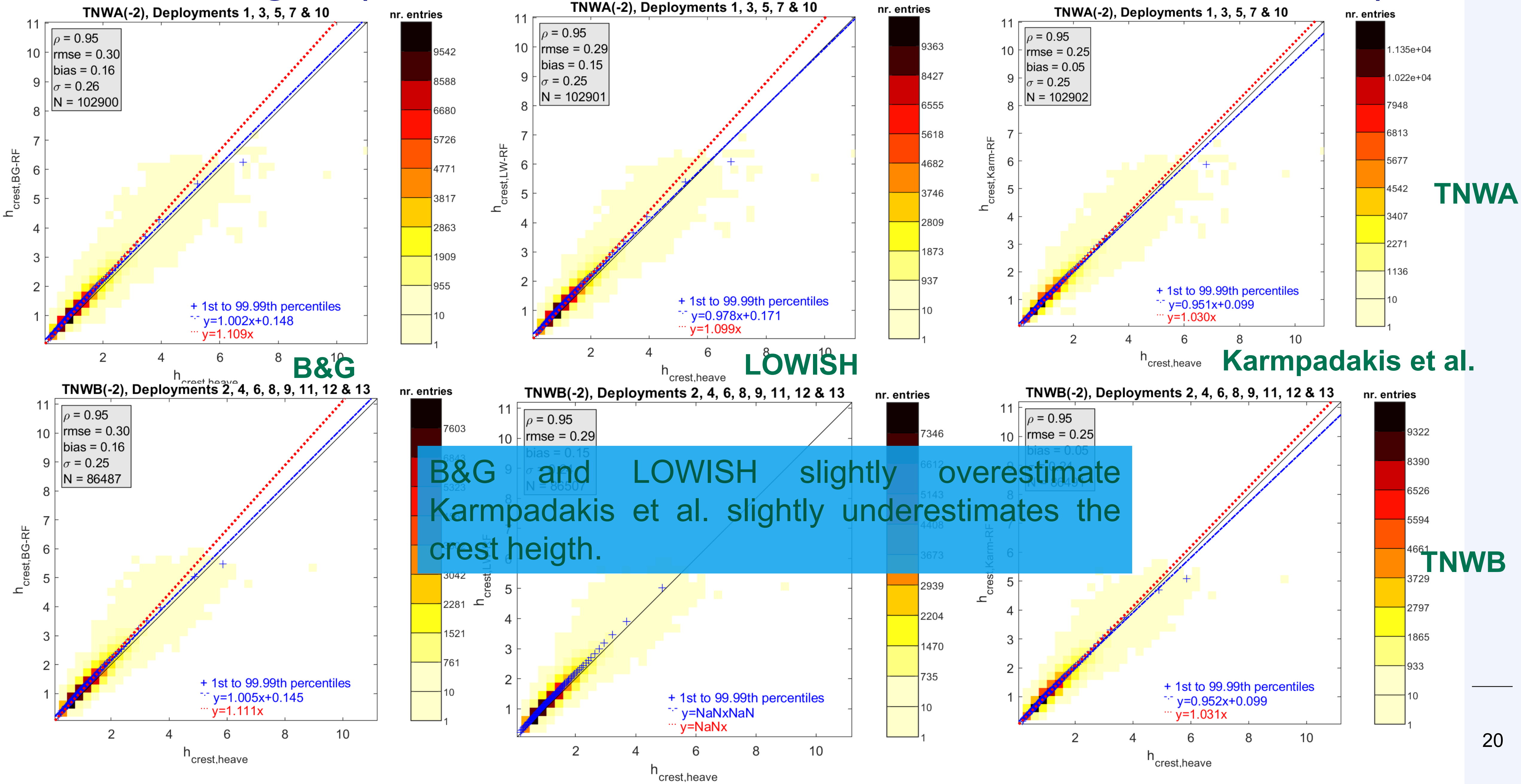


Karmpadakis et al. low bias. Slight underestimation of high H_{mo}

Crest height

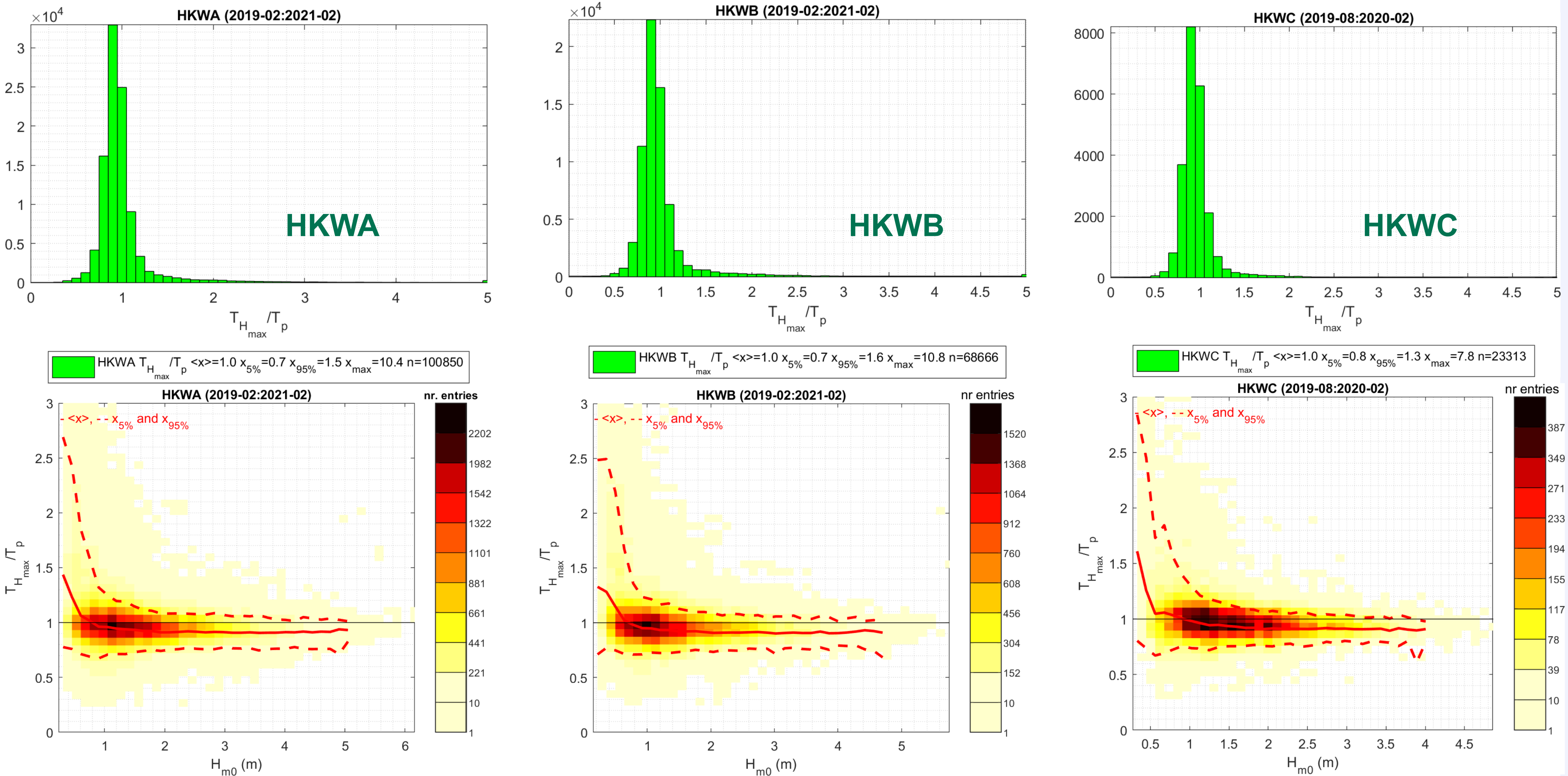


Crest height (determined using the Rienecker & Fenton method)

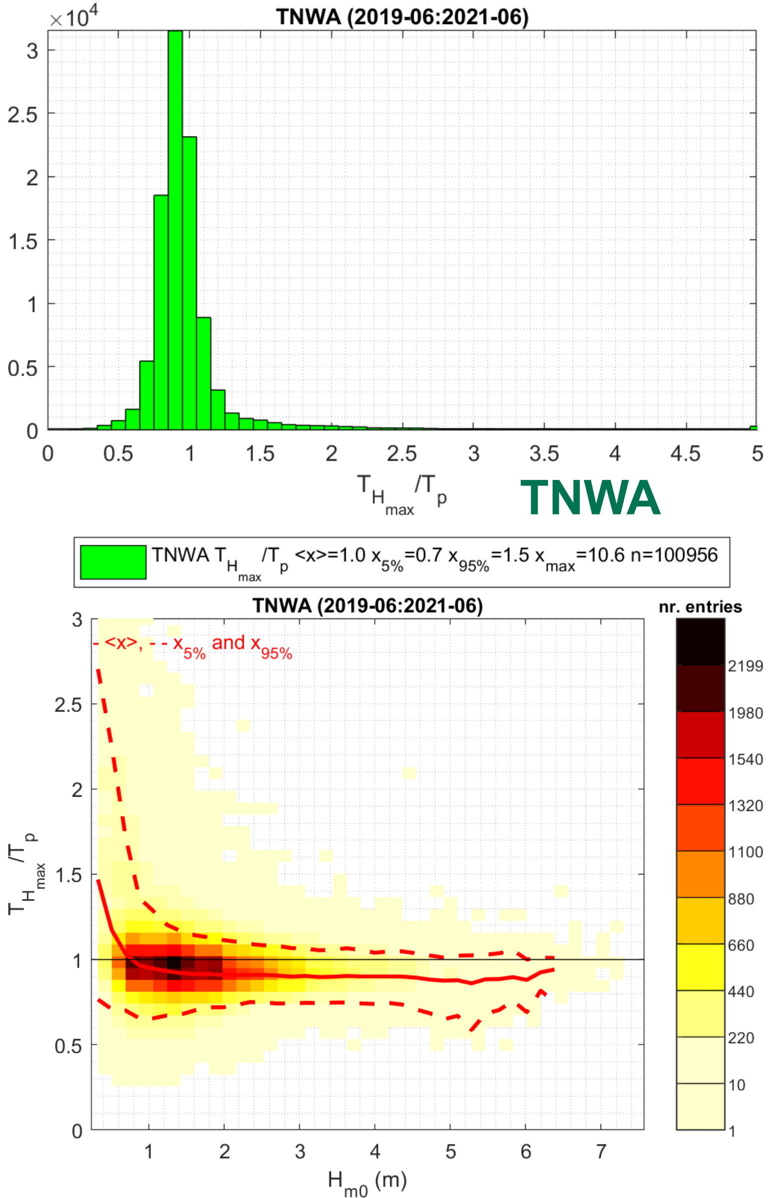


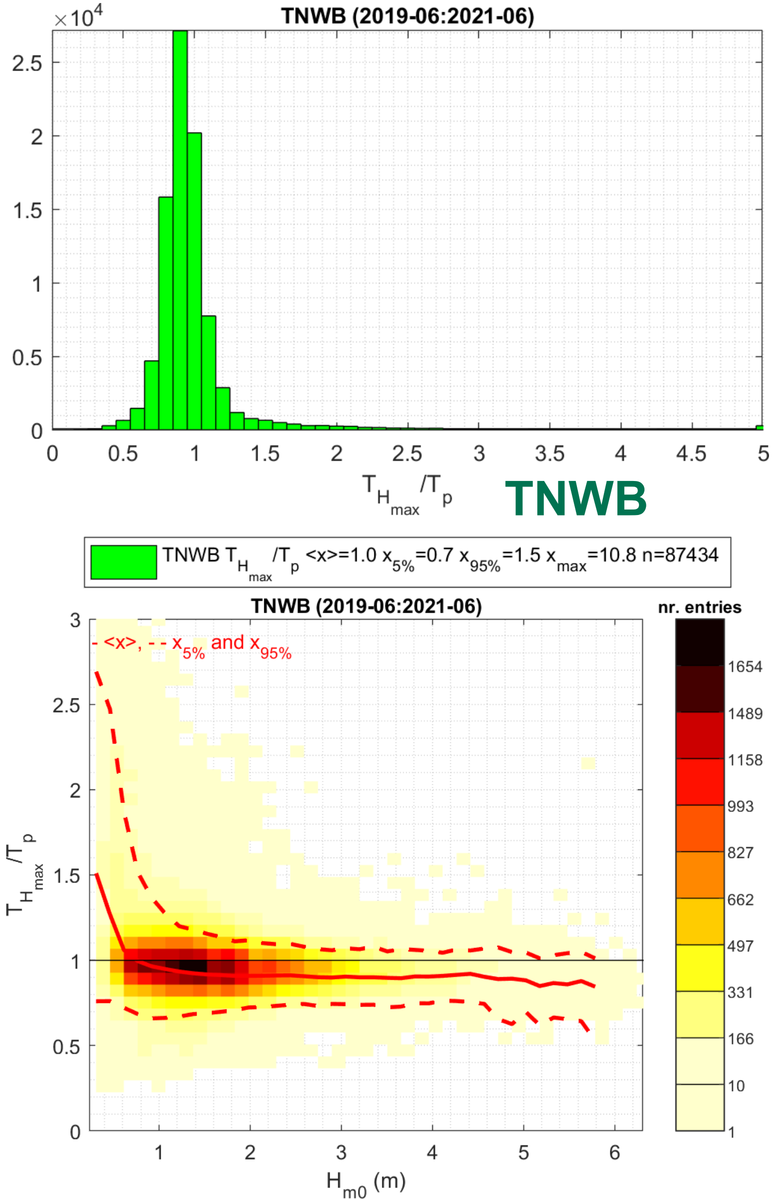
B&G and LOWISH slightly overestimate Karmpadakis et al. slightly underestimates the crest heigth.

Observed relation between T_{Hmax} and T_p



Observed relation between T_{Hmax} and T_p





The mean T_{hmax}/ T_p ratio is slightly lower than 1

Conclusions

1st Goal: Verify whether the deviations from the Rayleigh distribution are also observed in offshore wind zones and whether the use of the B&G dist. Is justified.

Maximum wave height and associated crest height - The estimates of LOWISH and B&G lead to conservative results, although less conservative than those of the Rayleigh distribution. The estimates of Karmpadakis et al. appear to be the most accurate, although slightly underestimating.

->Given the large uncertainties, the application of the B&G distribution is considered acceptable.

2nd Goal: Verify whether T_{Hmax} can be considered approximately equal to T_p

Period of maximum wave height – The results of Goda (1978) are in line with the data from the offshore wind measurement campaigns => $\left\langle \frac{T_{Hmax}}{T_p} \right\rangle \approx 1.$

->The assumption of $T_{Hmax} = T_p$ is considered acceptable.

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